Exp.-Nr. A2-1/05
Eingang: 26.8.05
an PAC:

Mainz Microtron MAMI

Collaboration A2: "Real Photons"
Spokesperson: A. Thomas

Proposal for an Experiment

'Measurement of the in-medium ω mass

Collaborators :

CrystalBall@MAMI collaboration

Spokespersons for the Experiment :
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Abstract of Physics :
After a successful pioneering experiment with the CBELSA/TAPS detector at ELSA (Bonn) this proposals aims at a detailed study of the in-medium properties of the omega meson at MAMI C. Using the Crystal Ball /TAPS setup, an improved second generation experiment with much higher statistics is proposed. Of prime interest are possible structures in the in-medium ω spectral function, the in-medium width of the ω meson, and the momentum dependence of the ω-nucleus potential.

Abstract of Equipment :
The tagged photon beam provided by MAMI C and the Glasgow-Edinburgh-Mainz tagging spectrometer will be used to measure ω photoproduction off nuclear targets. ω mesons will be registered through their $\pi^0\gamma$ decay in a 4π photon detector system comprising the Crystall Ball and the photon detector TAPS in a forward wall configuration.

MAMI–Specifications :

beam energy	1500 MeV
beam current	< 100nA
time structure	cw
polarization	unpolarized

Experiment–Specifications :

experimental hall/beam	A2
detector	Crystal Ball, TAPS, MWPC, PID
target material	liquid hydrogen, ^{12}C, ^{nat}Ca, ^{93}Nb,^{nat}Pb

Beam Time Request :

set–up without beam	—
set–up/tests with beam	24 hours (parallel with proposal A2/ ???)
data taking	1500 hours (parallel with proposal A2/ ???)

Measurement of the in-medium ω mass

August 12, 2005

Abstract

After a successful pioneering experiment with the CBELSA/TAPS detector at ELSA (Bonn) this proposals aims at a detailed study of the in-medium properties of the omega meson at MAMI C. Using the Crystal Ball /TAPS setup, an improved second generation experiment with much higher statistics is proposed. Of prime interest are possible structures in the in-medium ω spectral function, the in-medium width of the ω meson, and the momentum dependence of the ω-nucleus potential.

1 Introduction and motivation

The generation of hadron masses is one of the challenging questions in the non-perturbative regime of Quantum Chromodynamics. Hadrons are bound sytems of quarks. In case of other composite systems like atoms or nuclei, the mass of the total system is given by the sum of the masses of the constituents apart from very small binding energy effects. In contrast, e.g. the nucleon mass of 938 MeV is much larger than the sum of the current quark masses, estimated to be of the order of 15 MeV. The mass of the nucleon and of other light hadrons is explained in terms of energy stored in the motion of quarks and in the gluon fields. Thereby one obtains a massive system out of almost massless constituents: *mass without mass* [1, 2].

While this dynamic effect accounts for the bulk of the nucleon mass it is not the only source of hadron masses. Another contribution stems from the spontaneous breaking of chiral symmetry which is a fundamental symmetry of QCD in the limit of vanishing quark masses. If chiral symmetry were to hold also in the hadronic sector we would expect the existence of mass degenerate chiral partners, i.e. hadronic states with the same mass, the same spin but opposite parity. This is not realized in nature; chiral symmtery is broken: the ground state $1/2^+$ of the nucleon has a mass of 938 MeV while the lowest $1/2^-$ state, the $S_{11}(1535)$ nucleon resonance, has a mass of 1535 MeV. The lowest excited state of the nucleon $\Delta(1232)$ with $J^p = 3/2^+$ and the $D_{13}(1520)$ $J^p = 3/2^-$ nucleon resonance are separated in mass by 290 MeV. The mass split for these pairs of states amounts to several hundred MeV and is thus almost of the same order of magnitude as the nucleon mass, demonstrating the impact of chiral symmetry breaking on hadron masses. Similar mass gaps are observed in the meson sector: vector mesons: ρ ($J^p = 1^-, 776$ MeV) and a_1 ($1^+, 1260$ MeV); scalar modes: $\pi(0^-$,135 MeV) and σ ($0^+, 600$ MeV).

As described in detail by Weise, and Thomas and Weise [3, 4], hadrons are considered excitations of the QCD vacuum which has a complex structure of condensates of quark-antiquark pairs and gluons. As shown in Fig 1 the observed spectrum of low-mass hadrons has a characteristic mass gap of about 1 GeV which is closely linked to the non-vanishing quark condensate $< \bar{q}q >$, the ground state expectation value of the scalar quark density. This condensate is an order parameter for the spontaneous breaking of chiral symmetry in low-energy strong interactions. As Goldstone bosons of the spontaneously broken symmetry, the masses of light pseudoscalar mesons would vanish. Explicit symmetry

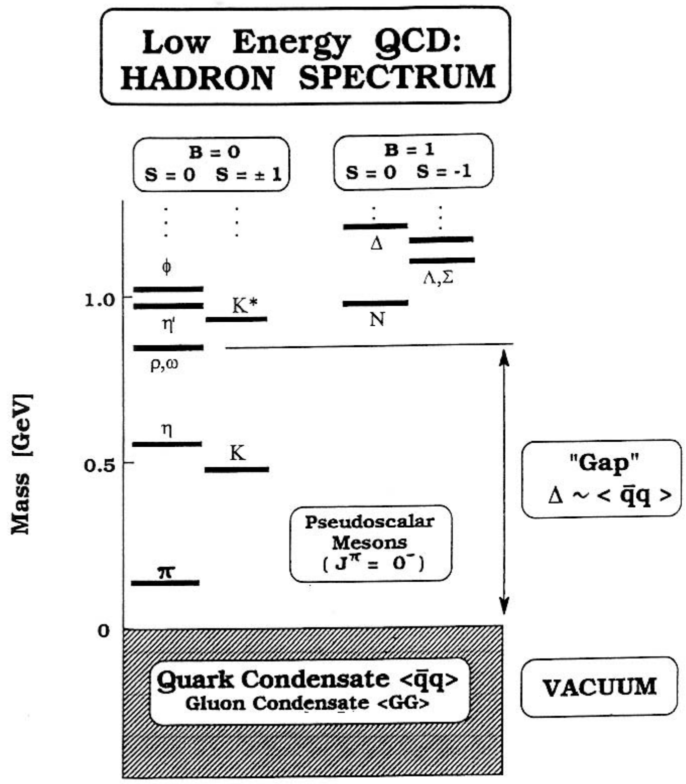

Figure 1: Hadrons as excitations of the QCD vacuum. The figure is taken from [3].

breaking by the masses of light current quarks introduces perturbations on a scale small compared to 1 GeV, leading to pseudoscalar meson masses within this mass gap.

The QCD groundstate also contains in addition other, higher order condensates. In a nuclear medium, characterized by temperature and/or baryon density, all these condensates are expected to change [5, 6]. As a consequence, changes in the hadronic excitation energy spectrum are to be expected. Hadron masses are, however, not directly related to these condensates which are no direct physical observables. The link between hadron masses and the $< \bar{q}q >$ and higher order condensates is provided via QCD sum rules [6, 7].

These theoretical concepts have initiated detailed theoretical studies and widespread experimental activities to search for in-medium modifications of hadrons. Experiments are being performed at several accelerators in the few GeV energy range trying to clarify whether hadron masses are indeed changed if produced in the nuclear medium. The main motivation for this experimental program is to achieve a better understanding of the origin of hadron masses in the context of spontaneous chiral symmetry breaking in QCD and their modification due to chiral dynamics and the partial restoration of chiral symmtery in a hadronic environment.

2 In-medium behaviour of vector mesons

2.1 Status of the field

In-medium modifications of vector mesons have been investigated theoretically by a number of groups. As an example, predictions by the Munich group [8] are shown in Figure 2. These calculations have been performed in the framework of an extended vector meson dominance model which incorporates the relevant features of chiral dynamics in

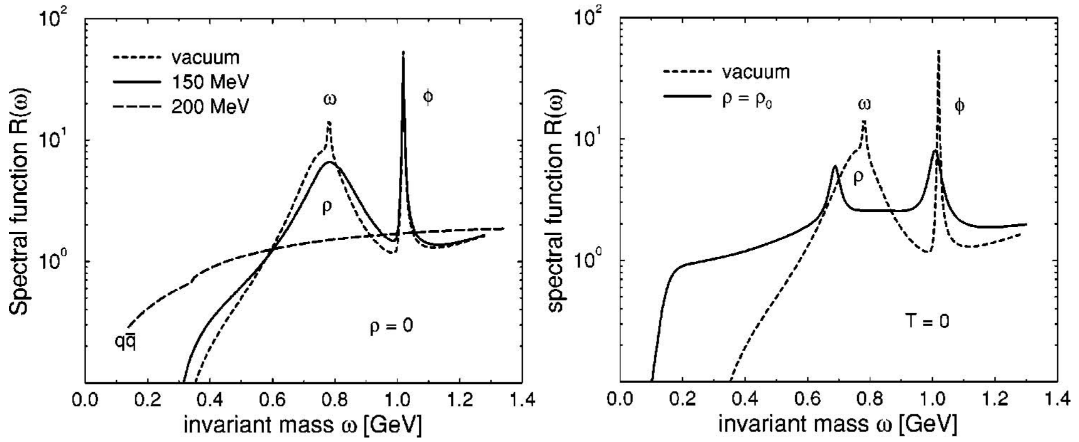

Figure 2: Vector meson spectral function (left) for different temperatures at vanishing baryon density as well as (right) for vanishing baryon density and normal nuclear matter density at temperature T=0. The calculations have been performed by Renk et al.[8].

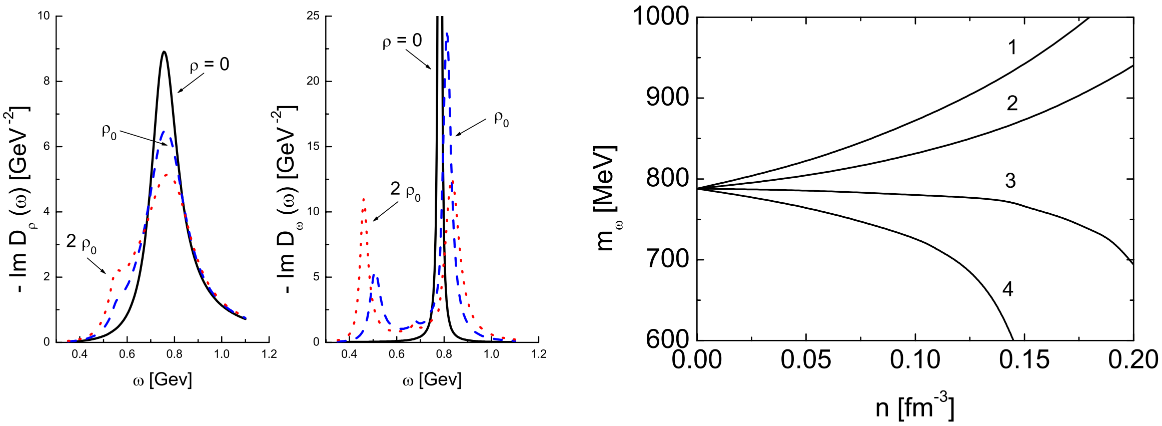

Figure 3: Left: spectral function of the ρ and ω meson as predicted by Lutz et al. [10]. Right: ω mass as a function of baryon density for different assumptions of the density dependence of the 4-quark condensate [14].

many body systems of interacting hadrons [9]. For vector mesons at rest in the nuclear medium, the vacuum spectral distribution (dashed curves) is modified either by heating or compressing the nuclear matter. While the ρ meson is dissolved at sufficiently high temperatures and densities the ω meson retains its character as a quasi-particle but exhibits a strong mass shift and broadening; due to its weak interaction with the medium the Φ meson, on the other hand, is expected to show only some broadening and almost no mass shift.

Other calculations like the ones by Lutz et al. [10] (see Fig. 3, left) and several other groups (e.g., [11, 12, 13]) predict structures in vector meson spectral functions due to coupling of these mesons to nucleon resonances. Applying QCD sum rules, Zschocke et al. [14] expect an upward or a downward in-medium mass shift for the ω meson, depending on the density dependence of the 4-quark condensate as shown in Fig. 3, right.

This variety in theoretical predictions - only some examples have been given - calls for experimental verification. A broad range of nuclear reactions is at the disposal of the experimentalists. The properties of vector mesons as a function of temperature T can be studied in relativistic and ultra-relativistic heavy ion reactions with increasing incident energy. Medium modifications at T=0 and normal nuclear matter density are experimentally accessible in photonuclear or elementary hadronic reactions. Here, the medium effects are only in the 10-30% range. They can, however, be measured quite accurately and theoretically interpreted in a relatively straight forward way. In heavy-ion reactions, the expected medium modifications are much stronger but the experiment integrates over the complex space-time history of the reaction which makes the interpretation more complicated since the density in the collision zone varies strongly with time.

The best approach to study in-medium properties of mesons is to observe their decay within cold nuclei. Lepton pairs as decay products have the advantage that they do not undergo strong final state interactions within the medium. The invariant mass of the meson within the medium can be determined from the measured and undistorted 4-momentum vectors of the leptons from

$$m_{meson} = \sqrt{(p_1 + p_2)^2}. \tag{1}$$

If this invariant mass differs from the in-vacuum mass of the meson, e.g. as listed by the particle data group [15], an in-medium effect has been observed. Lepton spectroscopy is thus the preferred experimental tool dispite of the extremely small branching ratios of vector mesons into dileptons of the order of $10^{-5} - 10^{-4}$. One has, however, to ensure that the observed decays really occur in the nuclear medium. This can be achieved by requiring sufficiently low recoil momenta of the respective mesons which can be deduced from the measured dilepton momenta.

Experimental investigations of in-medium properties of vector mesons have been pioneered by the CERES collaboration [16, 17, 18] at CERN who studied dilepton emission in ultra-relativistic nucleus-nucleus collisions. Calculations assuming only a broadening or a shift and broadening of the ρ meson spectral function [19, 20] are in good agreement with the data while estimates ignoring these medium effects fail to reproduce the experimental spectrum. These results provided the first evidence for medium modifications of vector mesons in heated nuclear matter.

Experiments to search for medium modifications of vector mesons at normal nuclear matter density have been performed or proposed at KEK, JLab, GSI, and ELSA. At KEK dilepton decays of ρ, ω, and Φ mesons have been investigated in proton-nucleus reactions at 12 GeV [21]. Evidence for medium modifications of the ρ meson has been deduced from a shift in the dilepton invariant mass spectrum for different nuclear mass numbers [22, 23]. A corresponding experiment using a photon beam has been performed at Jlab and is presently being analyzed [24]. At GSI, it has been proposed to use a pion beam for almost recoil less production of ω mesons in a nuclear target [25]. The corresponding experiment will be performed with the dilepton spectrometer HADES as soon as sufficiently intense pion beams will be available at GSI.

2.2 First evidence for an in-medium modification of the ω meson

An alternative experimental approach to study the in-medium properties of the ω meson is the investigation of the decay branch $\omega \rightarrow \pi^0\gamma$. The advantage of this decay channel is the branching ratio of 9% which is three orders of magnitude larger than the dilepton decay. Furthermore, it is larger by two orders of magnitude than the $\rho \rightarrow \pi^0\gamma$ decay. A medium modification observed in the $\pi^0\gamma$ channel can thus be unambiguously assigned to the ω meson. The disadvantage of the $\omega \rightarrow \pi^0\gamma$ channel is a possible rescattering of the π^0 within the nuclear medium which changes the pion momentum and thus distorts the deduced ω invariant mass. This effect was studied in a detailed simulation by Messchendorp et al. [26] including recent parametrisations of the pion-nucleus interaction. Any pion rescattering proceeds predominantly through the formation of an intermediate Δ resonance. The momentum of the re-emitted pion is small, governed by the Δ decay kinematics, and - smeared by Fermi motion - mainly leads to small invariant $\pi^0\gamma$ masses far below the range of interest between 600 to 800 MeV. According to Messchendorp et al. [26] the

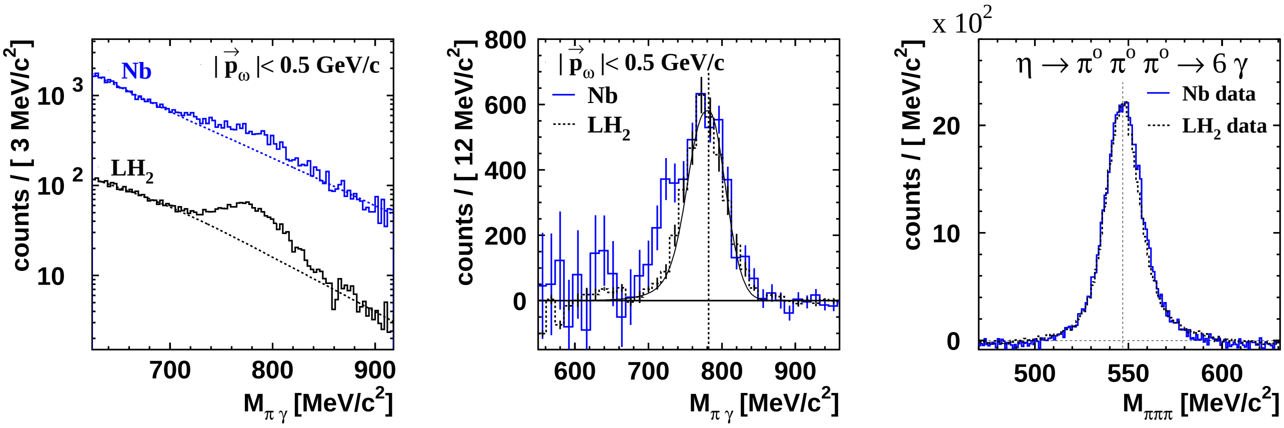

Figure 4: Left: $\pi^0\gamma$ invariant mass spectra for events with summed π^0 and γ momenta $\leq$ 500 MeV/c, measured for a LH_2 and a Nb target, respectively. Fits to the background are indicated by the dashed lines. Center: Same $\pi^0\gamma$ invariant mass distributions near the ω mass after background subtraction: Nb target (solid histogram); LH_2 target (dashed histogram). Right: Background subtracted invariant mass distribution for the long-lived η meson. Solid histogram: Nb; dashed histogram: LH_2 target. The figure is adapted from [27].

contribution to this mass range is of the order of some percent which can be even further reduced by removing all events with π^0 mesons of kinetic energies less than 150 MeV.

This approach has been followed in an experiment performed at the electron accelerator ELSA in Bonn [27]. The photoproduction of ω mesons on the proton and on Nb has been investigated in a comparative study. Bremsstrahlung photons in the range of 800 - 2600 MeV have been produced by the continuous wave electron beam from the electron stretcher ring ELSA impinging on a radiator wire. The photon energy $E_\gamma = E_e - E'_e$ is deduced event-by-event from the electron beam energy E_e and the energy E'_e of the scattered electron measured with a magnetic spectrometer (tagger). ω mesons have been identified via the $\omega \to \pi^0\gamma \to \gamma\gamma\gamma$ decay in an almost 4π photon detector system comprising the Crystal Barrel (1290 Cs(Tl) modules) as target detector and the photon spectrometer TAPS (528 BaF_2 modules) in a forward wall configuration.

2.2.1 The ω in-medium mass

Figure 4 shows $\pi^0\gamma$ invariant mass spectra in the ω mass range measured for a Nb and - for comparison - for a LH_2 target. Only events with ω meson momenta less than 500 MeV/c have been selected to enhance the fraction of in-medium decays. For long-lived, recoiling mesons like π^0, η, and η' no difference in the lineshape is observed for the two data sets since these mesons decay outside of the nucleus. As an example, this is demonstrated for the η meson in Fig 4 (right). In contrast,after background subtraction a deviation from the LH_2 target lineshape is found for ω mesons produced on Nb. The structure on the low mass side of the ω signal is attributed to in-medium decays of ω mesons of reduced mass.

More recently a corresponding analysis of data taken with a carbon target has been performed [28]. The resulting ω mass distributions for C and Nb are compared in Fig. 5 to coupled channel transport model calculations [29] which assume a drop of the ω mass according to

$$m = m_0(1 - 0.16\rho/\rho_0) \tag{2}$$

and an in-medium broadening of the ω meson to 40 MeV at normal nuclear matter density. The overall shape of the measured ω signal is reproduced, supporting the evidence for an

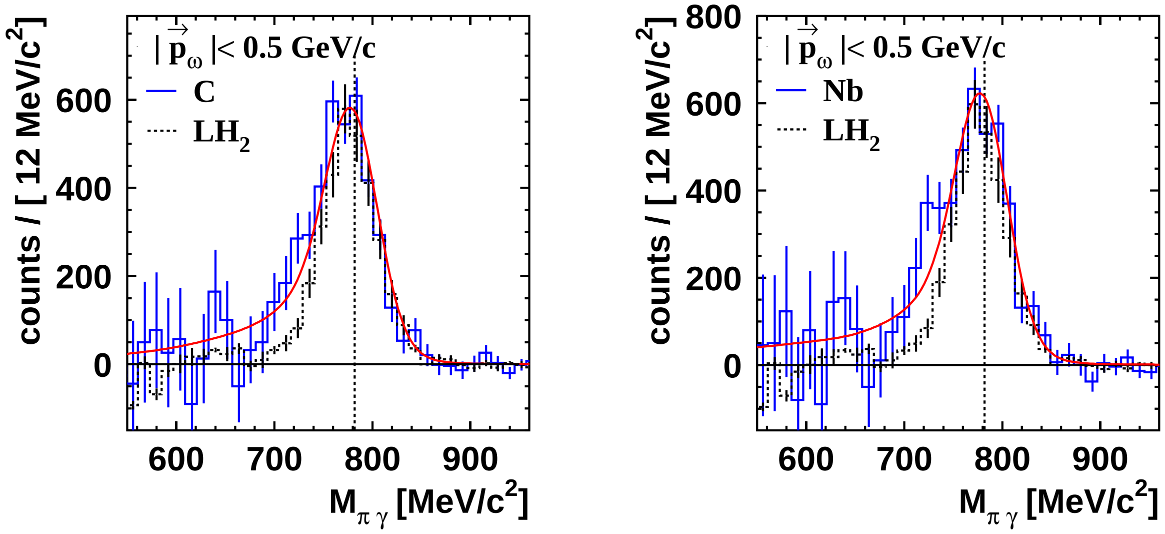

Figure 5: $\pi^0\gamma$ invariant mass spectrum for photonuclear reactions on a C (left) and a Nb (right) target. The experimental data of Trnka et al. [27] are compared to calculations within a coupled-channel transport model [29].

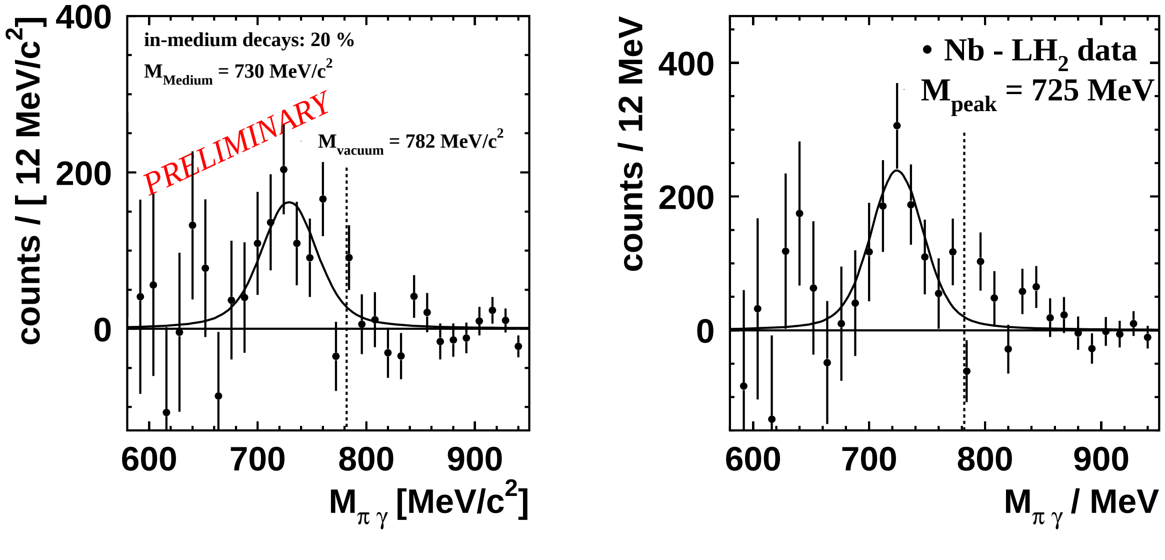

Figure 6: In-medium omega mass distribution for ω momenta ≤ 500 MeV/c for carbon (left) and niobium (right) at estimated average nuclear densities of $\rho/\rho_0 \approx 0.45$ and ≈ 0.55, respectively. The contribution of ω decays in vacuum has been subtracted (see text).

in-medium lowering of the ω mass. Although not statistically significant, there may be deviations from the smooth lineshape predicted theoretically. This is of interest in view of predicted structures in the spectral function which may arise from the coupling of the ω meson to nucleon resonances (see Fig 3). It is evident that a second generation experiment with significantly improved statistics - as proposed here - will have to resolve this question.

In Fig. 6 an attempt has been made to remove the contribution of ω decays in the vacuum to directly obtain information on the in-medium ω mass distribution; the in-vacuum-decay contribution, indicated by the dashed histogram in Fig. 5 has been subtracted after normalization to the right hand side of the ω signal. A fit to the resulting mass spectra gives peak positions of 730 MeV (C) and 725 MeV (Nb) for ω mesons at estimated average densities of about 45% and 55% of normal nuclear matter density, respectively. Again a cut on ω momenta less than 500 MeV/c has been applied to enhance the fraction of in-medium decays. The normalization procedure introduces a systematic error estimated to be within -5 to +30 MeV. This uncertainty mainly reflects different assumptions on the subtraction of ω meson decays in vacuum. The fraction of these decays was varied within a broad range from 80% to 45%. The case with 45% corresponds to the upper bound of the systematic uncertainty (+35 MeV) (for details see [27]). This result implies an in-medium drop of the ω mass by about 60 MeV. Extrapolation to normal nuclear matter density leads to a lowering of the ω mass by 14%, consistent within errors with the value deduced above from the comparison of the experimental data with the BUU calculations of Mühlich et al. [29, 30].

This result is taken as first evidence for a medium modification of the ω meson. As noted above, the experimental result is of special theoretical importance since Zschocke et al. [14] have pointed out that the ω mass is particularly sensitive to the density dependence of higher order quark condensates. The experimentally determined in-medium ω mass is thus a critical testing ground for our current understanding of the origin of hadron masses.

2.2.2 The ω in-medium width

The present quality of the data does not allow for a reliable extraction of the in-medium width of the ω meson from a fit to the invariant mass distributions of Fig. 6. The widths of the distributions are dominated by the experimental resolution. An alternative access to the in-medium width of vector mesons has been proposed by Magas et al. [31] for the case of the Φ meson. The broader the width of the vector meson because of additional inelastic channels within the medium, the smaller will be the number of Φ mesons escaping from the nuclear target. Experimentally, Ishikawa et al. [32] find a stronger than expected decrease of the Φ cross section with the nuclear mass, indicating a larger in-medium broadening of the Φ meson than theoretically predicted. Adapting this idea for ω mesons, P. Mühlich [33] has performed a corresponding calculation with a coupled channel transport code. Preliminary data taken by the CBELSA/TAPS collaboration [28] are compared to his reults in Fig.7 where the transparency ratio is plotted, defined by

$$T = \frac{\sigma_A}{A \cdot \sigma_N}. \tag{3}$$

The comparison suggests again a rather large in-medium width of ≥ 55 MeV for the ω meson. This conclusion will have to be confirmed by measuring more targets, in particular with large mass number, as proposed here. For a correct normalization of the transmission ratio the production cross section on the neutron has to be known as well; this requires an additional run on a deuteron target.

2.2.3 The momentum dependence of the ω-nucleus potential

Furthermore, the dependence of the ω signal on the ω momentum has been studied. It is expected that only low-momentum ω mesons (with a corresponding low velocity) decay

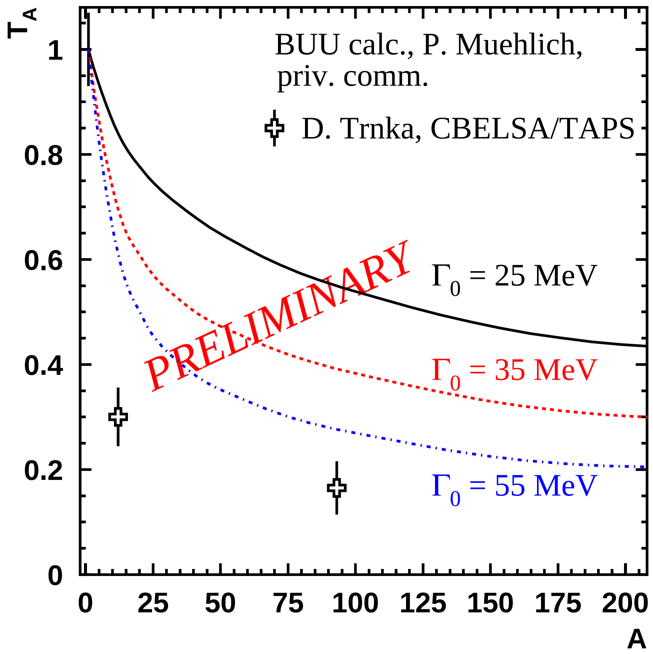

Figure 7: Transparency ratio as defind by eq.2 as a function of the nuclear mass number A. Curves represent calculations with a coupled channel transport code [33] asssuming different in-medium width Γ_0 for vanishing omega momenta. Preliminary experimental results by Trnka et al. [28] are shown for comparison.

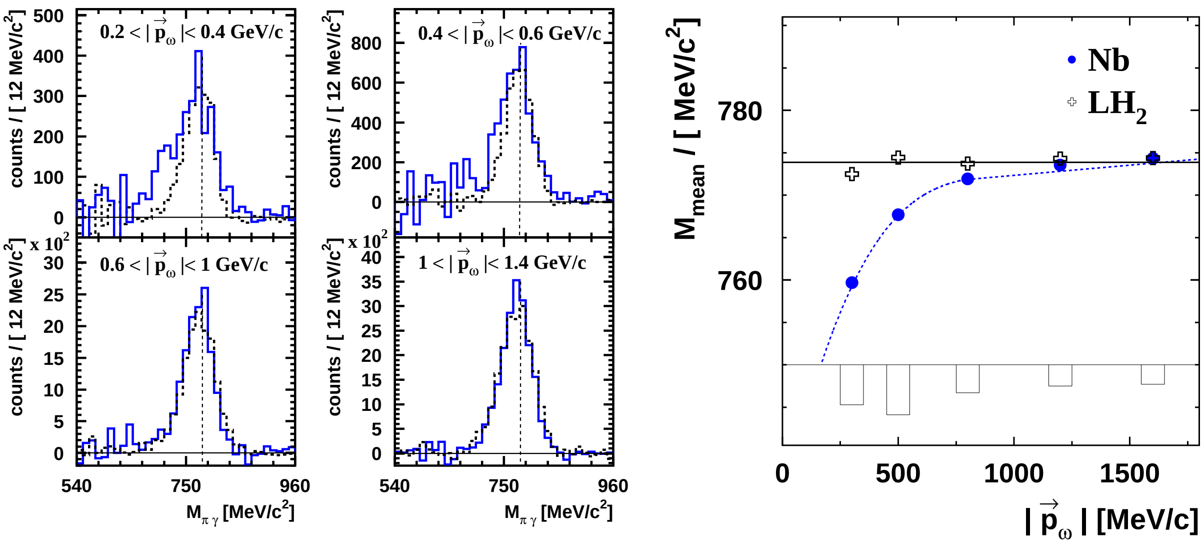

Figure 8: Left: $\pi^0\gamma$ mass spectrum after background subtraction and FSI suppression ($T_{\pi^0} > 150$ MeV) for different ω momentum bins. Solid histogram: Nb data, dashed histogram: LH_2 data. Right: Mean value of the $\pi^0\gamma$ invariant mass as a function of the ω momentum at an estimated average density of 0.6 ρ_0 for the Nb data (circles) and the LH_2 data (crosses) along with a fit.

inside the nucleus and carry information on the in-medium properties of the ω meson. The left panel of Fig. 8 shows the $\pi^0\gamma$ invariant mass distribution after background subtraction and FSI suppression ($T_{\pi^0} > 150$ MeV) for different ω-momentum bins. A pronounced modification of the lineshape is only observed for ω momenta in the range of 200 MeV $< \mid \vec{p_\omega} \mid <$ 400 MeV. The right panel of Fig. 8 shows the mean value of the mass distribution versus the 3-momentum of the ω meson for the LH_2 and the Nb data, indicating a momentum dependence of the extracted ω meson signal for the Nb data and a flat distribution, as expected, for the LH_2 measurement. In principle, this result might allow to extract the momentum dependence of the ω-nucleus potential. The limited statistics allows, however, only for a low number of momentum bins which makes it difficult to extract a quantitativ information. It is the aim of the proposed second generation experiment to provide sufficient statistics for a reliable extraction of the momentum dependence of the ω-nucleus potential.

3 Proposed experiment

With the proposed experiment we hope to extend our current knowledge of in-medium properties of ω mesons in 3 directions:

- is there a structure in the ω meson spectral function as suggested in some theoretical descriptions?
- can we extract information on the in-medium width of the ω meson from an analysis of the production cross section as a function of the nuclear mass?
- can we determine the momentum dependence of the ω-nucleus potential from a detailed measurement of the in-medium ω signal as a function of the ω momentum?

The experiment will be performed with the Crystall Ball/TAPS setup at MAMI C, shown in Fig. 9. With an electron beam of 1.5 GeV from MAMI C the upgraded Edinburgh-Glasgow-Mainz tagging spectrometer will provide photon beams of sufficient intensity in the required energy range of 1.0-1.4 GeV. It is this incident energy range for which the largest medium modifications of the ω meson are expected, as shown in Fig. 10.

3.1 Improvements

The proposed measurement is a second generation experiment and should thus significantly exceed in statistics the previous pilot experiment. To achieve this goal several improvements are suggested:

- **photon flux:** It is planned to exploite the higher photon flux at MAMI C. Previous experiments with the Crystal Ball/TAPS setup at MAMI have shown that the detector system tolerates photon fluxes of $8{\cdot}10^6$/s (Pb) to 13 $\cdot 10^6$/s (C) MeV which is about a factor two higher than the intensities at ELSA which were limited there by the electron beam intensity.
- **trigger:** Another advantage of the Crystal Ball/TAPS setup is that timing information is provided by all detector modules, allowing to include all detector segments in the first level trigger. Furthermore a cut on the sum energy in the Crystal Ball can be applied (see Fig.11) which is extremely usefull in reducing the first level trigger rate and in suppressing reactions which are not of interest in this experiment. The detection efficiency for the $\pi^0\gamma$ channel has been determined to 57% in a Monte Carlo simulation.
- **data acquisition:** Another improvement will be the higher data taking capability expected for the next round of experiments at MAMI. Although the usable luminosity will be limited by the detector system, this achievement will allow taking a larger data sample because of the reduced computer dead time.

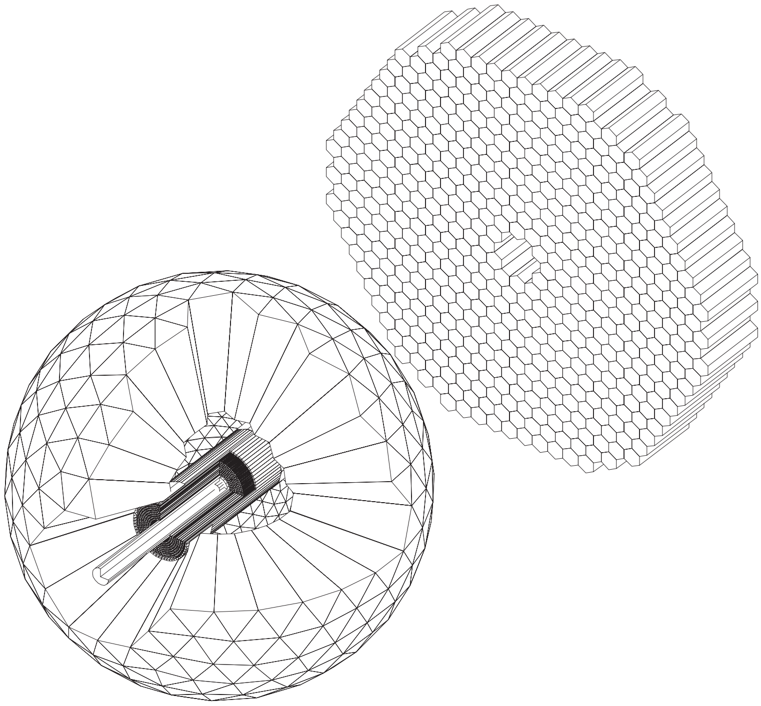

Figure 9: Experimental setup for the proposed experiment. The photon beam comes from the left. The Crystal Ball detector (comprising 672 NaI modules) and the TAPS forward wall (comprising 384 BaF_2 modules are combined to form an almost 4π photon detector system. The inner detector consisting of a cylindrical wire chamber and a segmented plastic scintillator serves for charged particle detection. At forward angles ($\leq 20^0$) charged particles are registered in plastic scintillators mounted in front of the individual BaF_2 modules.

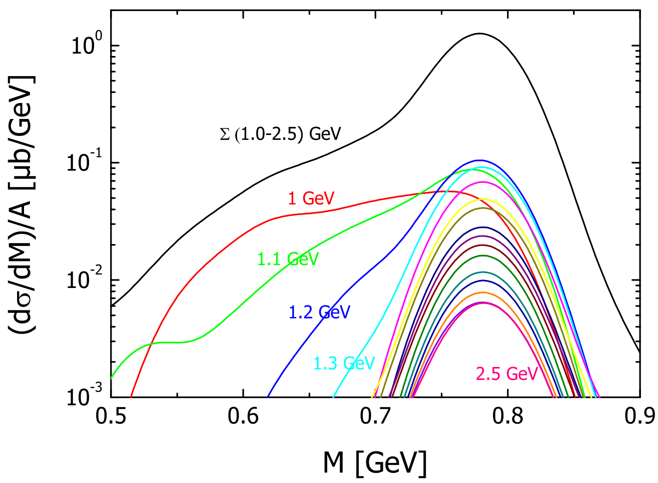

Figure 10: ω mass distributions predicted in a coupled channel transfer calculation [33] for different incident photon energies.

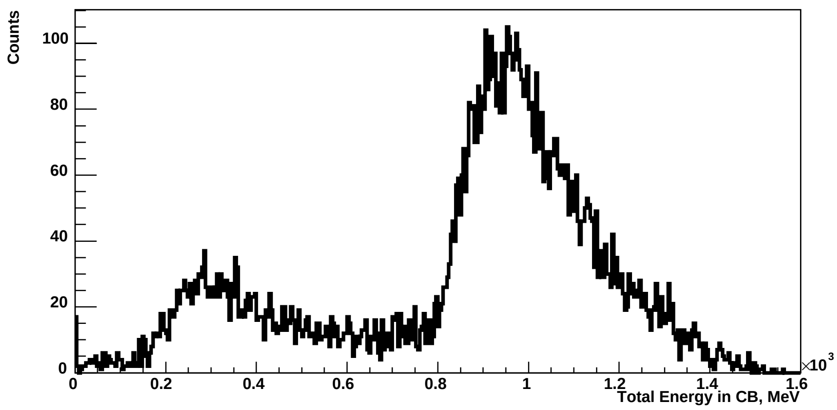

Figure 11: Monte Carlo simulation of the sum energy in the Crystal Ball for $\omega \to \pi^0\gamma$ events.

- **detector improvements:** The plastic detectors in front of the BaF_2 modules will be replaced by new ones which provide higher light output. With the new TAPS electronics the energy information from these detectors will be read out, thereby improving the particle identification capability and photon/particle discrimination at forward angles.
- **running times:** In addition, running times are requested which are about a factor 2 longer than in the pilot experiment at ELSA. This should give an overall improvement factor of approximately five which is sufficient to answer the main 3 questions given above. The requested running times, proposed targets, and expected rates are given in the subsequent table.

targets	p	d	C	Ca	Nb	Pb
photon flux (0.7-1.4 GeV) [$10^6/s$]	13	13	13	11	10	8
target thickness [cm]	5	5	2	1	0.1	0.06
running time [h]	100	100	100	100	400	500
number of events			20 000	10 000	20 000	4500
effective number of events			3 600	1500	3 600	450

The effective number of events S* takes the signal to background ratio S/B into account according to $S^* = \frac{S}{1+\frac{2B}{S}}$.

The total requested running time is

1300 hours.

The run on the deuteron target is important for extracting the cross section on the neutron. This information is essential for determening the the transparency factor (eq. 3 and Fig. 7) which is normalized to the cross section on the nucleon.

The number of expected events are scaled up by a factor 5 from the number of events observed in the pilot experiment at ELSA. With this statistics it will be possible to have 4-5 momentum bins below 600 MeV/c for studying the momentum dependence of the ω signal. If the structure in the ω spectral function (see Fig.5) at about 630 MeV is real one would expect there about 1500 counts ($S^* = 40$ counts) for each target.

Acknowledgements

The close colaboration with Pascal Mühlich from the Giessen theory group has been essential for the preparation of this proposal. Illuminating discussions on the planning and theoretical interpretation of the proposed experiment with Ulrich Mosel, Eulogio Oset, and Wolfram Weise are highly appreciated.

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